Chapter 1
Soil Heterogeneity and Crop Growth

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Abstract Producers around the world are considering the use of precision agriculture technologies. One of the key factors encouraging this development is the spatially varying performance of agricultural crops. In many instances, yield variability can be associated with differences in soil attributes across agricultural fields. Understanding and managing spatial variability in soils has become one of the main strategies to optimize crop production, based on local needs for fertilizer, lime, water and/or other crop production inputs. This chapter presents some basic concepts related to the formation of soil heterogeneity and discusses several ways agriculturists can account for spatial variability in soils through differentiated cultural practices and management.

1 Sources and Scales of Soil Heterogeneity

Since the last decade of the twentieth century, agriculturalists have become increasingly interested in using information-based agriculture for agronomically and/or economically optimized crop production systems (Sonka et al. 1997). One of the most obvious strategies is site-specific management, or, more generally, precision agriculture (Pierce and Nowak 1999), earlier termed farming by soil (Robert 1993). To see the reasons soil variability is linked with inconsistent crop performance, it is important to understand what causes even the best-managed agricultural fields to provide significantly different growing environments from one location to another (Webster 2000, McBratney et al. 2003).

The initial factors influencing variability in soils are related to five soil-forming characteristics: parent material, climate, topography, organisms (including vegetation) and time (Jenny 1941). These factors result in soils which are unique and varied on several scales – global, regional, among and within fields, down to the soil

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E.-C. Oerke et al. (eds.), *Precision Crop Protection - the Challenge and Use of Heterogeneity*, DOI 10.1007/978-90-481-9277-9_1,

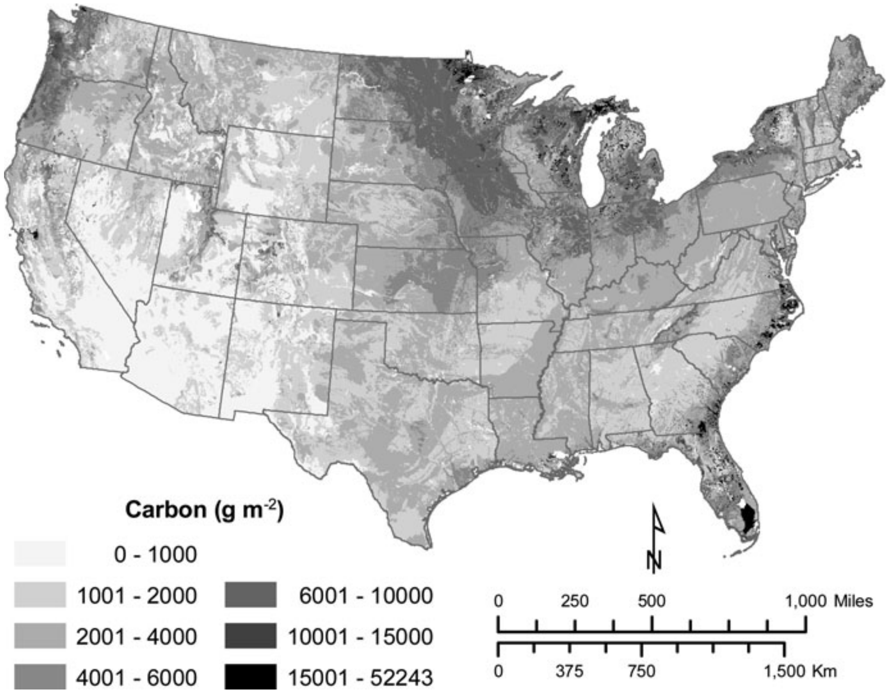


Fig. 1.1 Organic carbon in the top 1 m of soil throughout the contiguous United States provides an example of soil heterogeneity on a regional scale.
Source: United State Department of Agriculture Natural Resources Conservation Service, State Soil Geographic Database (STATSGO)

aggregates. These naturally occurring sources of variability dominate as primary influences on soil heterogeneity on global and regional scales. Figure 1.1 provides a good example, illustrating soil organic carbon in the top 1 m of soil across the continental United States. Soil organic carbon tends to be higher in regions with cool and/or wet climates, as well as in areas dominated by forest or prairie vegetation. It is lower in hot, dry regions.

On the field and sub-field scales, naturally occurring variability can remain quite significant, but historic management enters in as another important factor influencing variability. Figure 1.2 is an example of both natural and management factors affecting soil properties – in this case, soil color, which relates to soil organic matter and productivity in general. Located near the Platte River in central Nebraska, the field contains alluvial soils, with patterns associated with repeated flooding and deposition of sand and silt. The background aerial image obtained in the mid-1950s can be used to identify field areas with relatively light and dark soils, originating from both natural processes as well as management. Some patterns of darker soil are irregular or curved, resulting from silt deposition. Other patterns of darker soil are regular and linear, resulting from historic use of the land. In this case, the lighter-colored block in the eastern part of the image is an old field tilled and leveled

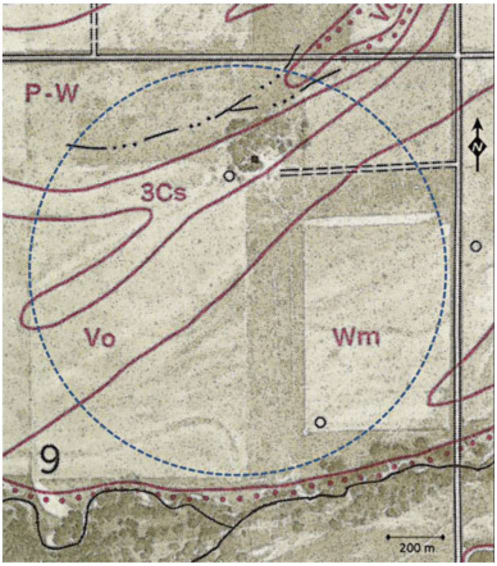


Fig. 1.2 Aerial image and soil series boundaries for a field in Hall County, Nebraska, USA. Vo = Volin silt loam; Wm = Wann loam; 3Cs = Cass fine sandy loam, deep; P-W = Platte-Wann complex.
Source: Hall County Nebraska Soil Survey, United States Dept. of Agriculture, January 1962. The *dashed line* represents the current field boundary

for furrow irrigation in the mid-1950s or earlier. The darker soil region surrounding this block was not tilled until the mid-1980s. Consequently, the portion of the field with a longer tillage history contains about half the soil organic matter of the more recently tilled soil. This image illustrates field boundaries which may be evident in patterns of crop growth many years later, when the entire field within the dashed outline is managed as one unit.

Applying soil amendments such as fertilizer and lime can also impact the heterogeneity of soil properties. The effects can be short-lived or persistent. Figure 1.3

Fig. 1.3 Aerial image of a furrow-irrigated maize field at V12 growth stage, Clay County, Nebraska, USA

illustrates both natural and management-induced patterns of crop nitrogen status. As nitrogen in soil is very dynamic, heterogeneity in soil's N supply is dynamic as well. Light areas within this field are deficient in crop nitrogen, while darker areas have an adequate supply of nitrogen to meet crop requirements at this growth stage. Irregular, curved patterns of N deficiency are associated with lower landscape positions in the field where water accumulated and caused denitrification. The regular, linear stripes across the field are the result of uneven nitrogen fertilizer application. Darker stripes received more fertilizer; lighter stripes received less. These regular patterns of uneven fertilizer application are more pronounced in lower/wetter areas of the field, where denitrification was greater.

Figure 1.4 is another example of management-influenced soil heterogeneity. Currently, this field is managed as a 60 ha center-pivot irrigated field. This field was subdivided into 11 smaller fields. At one time, a farmstead was located in the southwest corner of the field. Livestock manure was spread on the field nearest the farmstead. As a result, substantial immobile nutrients accumulated in places where the manure application rate exceeded the rate of crop nutrient removal. Colored dots in Fig. 1.4 represent soil phosphorus (P) measurements, with soil P concentrations in the southwest corner exceeding 100 mg kg^{-1}. Patterns of soil P concentration throughout the rest of the field are to some degree associated with soil series patterns. The Blendon soil series (Bed and BedA) are lower landscape position soils than the Hord (Hd) soil series. The area of higher soil P associated with Blendon soils periodically has lower crop yields due to saturated soil following heavy rains and loss of plant population. The crop removes less phosphorus due to this saturation in some years, which leads to the gradual accumulation of fertilizer P.

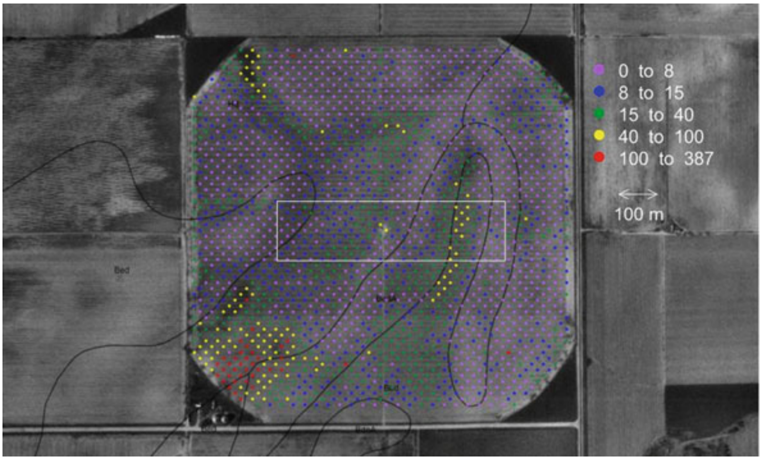
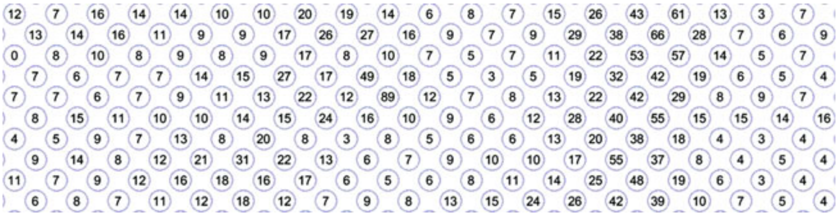


Fig. 1.4 Aerial image and soil series boundaries for a center-pivot irrigated field, Buffalo County, Nebraska, USA. Soil sample locations with Bray-1 P (mg kg^{-1}) concentrations in the upper 20 cm are superimposed

Figure 1.1 illustrates heterogeneity on the national scale; however, for purposes of crop management, variability on the field and sub-field scale are of greatest interest. Agriculturalists must sample thoroughly to accurately determine variability in the soil properties of interest. When designing a sampling procedure for the field, any known factors which may influence patterns of soil properties (e.g., historic manure applications or the former presence of a farmstead) should be considered. Figure 1.5 is a detailed section from the middle of the field illustrated in Fig. 1.4, showing trends in soil P concentration with samples collected every 24 m. Trends over distances of 100 m and greater are consistent with changes in soil series and topography; variability at distances of 50 m or less are more likely related to management.

Figure 1.6 illustrates soil P heterogeneity in both horizontal and vertical dimensions. Created using a transect sampling of a ridge-tilled row in 5 cm increments (horizontally and vertically), this graph illustrates the formation of a band of high soil P concentration. With ridge-till systems, the row location is maintained from year to year, often with repeated application of starter fertilizer at planting. Soil


12 7 16 14 14 10 10 20 19 14 6 8 7 15 26 43 61 13 3 7
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9 14 8 12 21 31 22 13 6 7 9 10 10 17 55 37 8 4 5 4
11 7 9 12 16 18 16 17 6 5 6 8 11 14 25 48 19 6 3 4
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Fig. 1.5 Transect subsection from Fig. 1.4, illustrating variability in soil Bray-1 P (mg/kg) concentration every 24 m

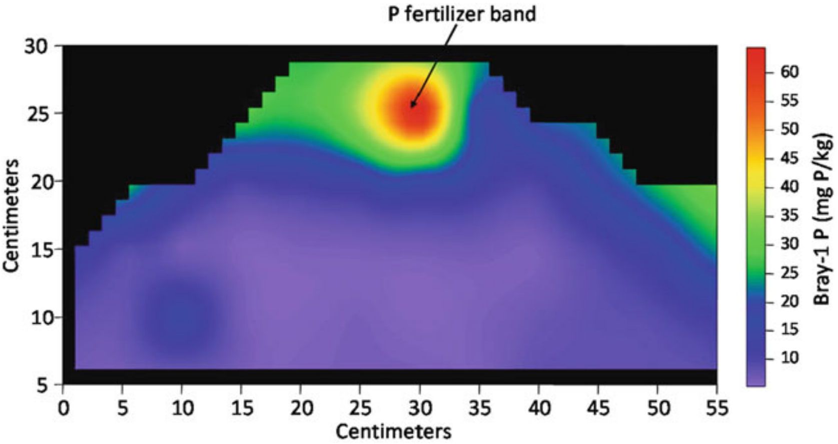

Fig. 1.6 Cross-section across a ridge-tilled row, of Bray-1 P concentration (Clay County, Nebraska, USA)

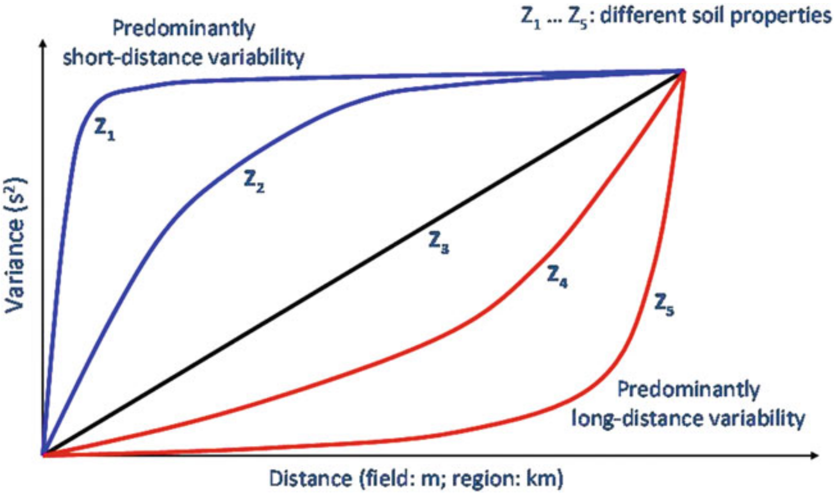

Fig. 1.7 Different potential relationships between sample distance and variance

P concentration varies significantly in both horizontal and vertical dimensions, but in a predictable pattern, given the history of ridge tillage and starter fertilizer use. Knowing this, the agriculturalist can derive a sampling technique which accurately represents the availability of soil P to the crop.

The spatial scale of variability for a given soil property of interest can differ with the property (Fig. 1.7). Some properties, such as soil nitrate, are highly variable over short distances (mm to m). Other properties, such as soil carbon, vary primarily over distances of m to km. Table 1.1 lists ranges of semivariogram models (measures of soil spatial structure) and coefficients of variation for several influential soil attributes (Mulla and McBratney 2000).

Soil properties can vary over time as well as space. Also, some properties are highly dynamic, changing rapidly with time, while other properties are relatively static, varying little from year to year. In assessing spatial variability, temporal variability can sometimes prove to be an important factor. Dynamic properties may change at different temporal scales as well. For example, at shallow depths, soil temperature follows one pattern diurnally and a different pattern seasonally. As depth increases, these patterns are dampened until at some depth temperature is almost constant. Other examples of highly dynamic properties are: soil moisture, microbial activity, water soluble salts, nutrient concentration in soil solution, and soil redox potential. Examples of relative static properties include: soil depth, texture, color, cation exchange capacity, and bulk density.

2 Methods of Assessment

To properly account for existing soil heterogeneity, agriculturalists must assess and interpret measures of mechanical, physical, chemical, biological and other phenomena related to various processes occurring within the root zone. Traditionally this

Table 1.1 Typical Variability of Soil Properties (Mulla and McBratney 2000)

Property	Range for semivariogram models [m]	Spatial dependency	Coefficient of variation [%]	Magnitude of variability
Saturated hydraulic conductivity	1–34	Short range	48–325	High
Percent sand	5–40	Short range	3–37	Low to moderate
Saturated water content	14–76	Short to moderate range	4–20	Low to moderate
Soil pH	20–260	Short to long range	2–15	Low
Crop yield	70–700	Moderate to long range	8–29	Low to moderate
Soil Nitrate-N	40–275	Moderate to long range	28–58	Moderate to high
Soil available potassium	75–428	Moderate to long range	39–157	High
Soil available phosphorous	68–260	Moderate to long range	39–157	High
Organic matter content	112–250	Long range	21–41	Moderate to high

has been accomplished through soil sampling (extracting a fixed amount of soil from a predefined depth) for off-site laboratory evaluation (Peck and Soltanpour 1990). Equipment and methodology used to conduct laboratory soil analyses continue to evolve, but a proper soil sampling scheme is equally important (Crepin and Johnson 1993, Tan 2005, de Gruijter et al. 2006).

To observe spatial heterogeneity in soils, samples from multiple locations within a landscape must be obtained. A model-based principle of sampling is the most promising when it comes to addressing spatial and temporal variability (de Gruijter et al. 2006). Geostatistical methods are used to analyse variability and to predict soil attributes in non-sampled locations using (Wollenhaupt et al. 1997). The major drawback of these conventional strategies is that a relatively coarse sampling density is often deemed most economical. This might not suffice to reveal true spatial variability in soils (McBratney et al. 2005).

To overcome the low spatial resolution of economically feasible sampling, both remote and proximal sensing technologies have been used. Remote sensing relies on acquiring imagery-type data using optical and radiometric sensors installed on an aerial platform or a satellite. Proximal sensing systems are placed near the surface or in contact with soil being tested. When proximal soil sensors are used while traveling across the landscape (on-the-go), geo-referenced data can be used as it is with yield maps to create high-density maps of sensor measurements.

The usefulness of remote sensing data in characterizing soil heterogeneity (Frazier et al. 1997, Leon et al. 2003) depends on spatial, spectral, radiometric and temporal resolution. Spatial resolution (pixel size) depends on the instrumentation and altitude of the measurement platform. Spectral and radiometric resolution also depends on the type of instrument and may be related to imagery that is panchromatic (having light reflectance integrated over the entire visual part of spectrum), multispectral (typically blue, green, red and near-infrared), or hyperspectral (typically more than 200 narrow spectral bands). Panchromatic and multispectral data suffice to visualize the overall spatial variability of soil reflectance. Hyperspectral data has been used to create various models used to predict individual soil parameters of interest (Christy 2008). Temporal resolution of remote sensing data relies on service availability. Images obtained on a clear day with minimal vegetation coverage have been viewed as the most suitable for soil heterogeneity analysis. When agriculturalists attempt to use remote sensing imagery to study soil variability, dense crop residue resulting from no-till crop production is a source of noise.

On-the-go proximal soil sensing systems can be deployed in direct contact with soil while mounted to a vehicle (Hummel et al. 1996, Sudduth et al. 1997, Adamchuk et al. 2004, Shibusawa 2006). The design concepts are many and varied, but most on-the-go soil sensors involve one of the following measurement methods: (I) electrical and electromagnetic sensors that measure electrical resistivity/conductivity or capacitance affected by the composition of the soil tested; (II) optical and radiometric sensors that use electromagnetic waves to detect the level of energy absorbed/reflected by soil particles; (III) mechanical sensors that measure forces resulting from a tool engaged with the soil; (IV) acoustic sensors that quantify the sound produced by a tool interacting with the soil; (V) pneumatic sensors that assess the resistance to the air injected into the soil, and (VI) electrochemical sensors that use ion-selective membranes producing a voltage output in response to the activity of selected ions (e.g., hydrogen, potassium, nitrate, etc.).

Ideally, a soil sensor would respond to the variability of a single soil attribute and would be highly correlated to a particular conventional analytical measurement. Unfortunately, in reality, every sensor developed responds to more than one soil property. Separating their effects is challenging; the process depends on many region-specific factors. Figure 1.8 provides a classification summary of the main types of on-the-go soil sensors with corresponding agronomic soil properties affecting the signal. In many instances, an acceptable correlation between the sensor output and a particular agronomic soil property was found for a specific soil type, or was achieved when the variation of interfering properties was negligible.

Remote and proximal sensing data provide low-cost, high-density information on spatial variability in soils. The resulting maps can be integrated along with digital field elevation maps to delineate field areas with significantly different crop production environments, and to prescribe locations for targeted soil sampling. Delineation of relatively homogeneous areas within fields using sensor measurements allows the producer to establish soil-based management zones (Fridgen et al. 2004, Simbahan and Dobermann 2006). Targeted soil sampling can be used to investigate whether soil properties of interest (e.g., soil nutrient content) relate significantly to field topography and/or sensor measurements. If such relationships are found, sensor measurements can be used to produce high-resolution maps of indirect predictions of different agronomic soil properties. For example, maps of apparent soil electrical conductivity (Allred et al. 2008) frequently reveal boundaries of soil series,

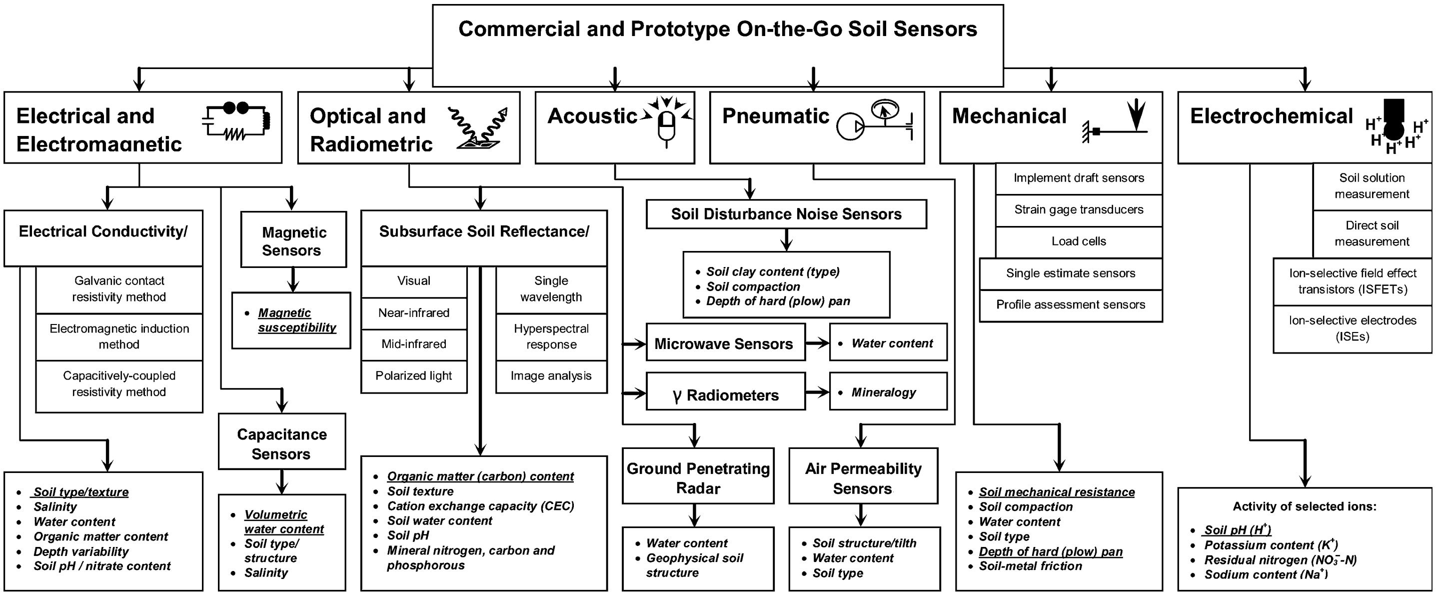

Fig. 1.8 Family of on-the-go soil sensing systems

including soil-forming anomalies such as eroded hillsides or landscape depressions. Because of the differences in yield potential – and therefore, nutrient uptake – it's logical to assume that certain nutrients may vary according to the same patterns (Corwin and Lesch 2003, Heiniger et al. 2003).

When looking at the family of remote and proximal soil sensing systems, it is important to remember that crops themselves are the most effective sensors indicating the quality of a local environment. The spatial distribution of the overall crop performance that in many instances can be explained by soil heterogeneity can be revealed by remote sensing imagery taken during vegetation stages, proximal sensing of crop canopy reflectance, and, ultimately, yield maps. Current precision agriculture research is focused on the integration of various sources of soil- and crop-based sensing technologies to discover and understand spatial variability of soil attributes limiting yield potential. Variable rate application of agricultural inputs according to local needs (economically optimized while considering spatially variable crop production potential) can be the means to increase profitability while preventing unnecessary environmental pressure in a given cropping system.

3 Spatially Differentiated Crop Management

Providing differentiated crop management according to soil variability is a matter of knowing what is manageable and what is not. As noted previously, spatial variability arises from different sources that generally fall into two broad categories: natural and management-induced. The natural sources of variability are primarily those associated with the soil formation processes. However, once we start managing land, we induce additional changes in the crop-growing environment. These changes can affect the soil, soil water, air, and soil temperature. The interactions among these factors, along with changes in weather, also cause variability sometimes attributed to soil heterogeneity.

Variability in soil properties can be categorized as either static or dynamic. The appropriateness of addressing these variations changes, depending on the probability of achieving a positive economic return and the justification for using the required time. Therefore, the list of economically manageable factors becomes operation-specific, dependent upon the resources available and the benefit-to-risk ratio. When producers begin to think about spatially differentiated crop management, they must first determine the types and levels of soil variability they have. In other words, they must ask which soil properties vary and how much? Secondly, producers must determine the size of a manageable area (under one acre or hectare of land versus large portions of a landscape). Regardless of the area of differentiated management, producers must develop a qualitative selection method to define the factors to be addressed. After the qualitative assessment, producers should carry out a quantitative evaluation that measures the degree of variability with respect to the available resources (money and time). It is also advisable to determine what is causing the variability and whether or not one can make a profitable change. In other words, will the increased income from site-specific management be significantly greater than the costs involved?

Differentiated field management requires a significant commitment of both time and money, including the cost of gathering and interpreting information as well as any add-on costs affiliated with site-specific management technology. Producers should consider seven steps: (I) data collection; (II) data management and storage; (III) data processing; (IV) data analysis; (V) data interpretation; (VI) synthesis of information; and (VII) decisions and changes in management.

All the changes in crop management fit into a decision framework made up of three categories: strategic, tactical and operational decisions. Generally, strategic decisions are those that will have effects lasting for 10 years or more. The economic impact is experienced over the long-term and, therefore, the payoff is distributed over many years. These decisions can affect not only current but future environmental considerations related to land and input management. The main question is whether the variability is great enough to warrant a change in management. Tactical decisions are those that have an impact during the coming 5 years. They may involve equipment as well as cropping systems, and may include data management. For instance, producers can delegate information processing to a professional service provider to give themselves needed time for farm-related work (marketing, equipment repair, record keeping, etc.). Operational decisions affect management during the upcoming year only. These primarily include: agronomic input needs, input costs and purchases, equipment maintenance, management of hired labor, etc.

Implementing spatially differentiated crop management assumes that additional information helps producers to make decisions that increase farming efficiency and/or reduce negative environmental impact. Bear in mind that ‘data’ and ‘information’ are not the same. The decision framework discussed above should illustrate that differentiated field management frequently requires additional time and monetary investments. As producers approach making changes in their management process, they must determine which factors are most important. According to Covey (1998) one must take care of the ‘big rocks’ before one worries about the ‘pebbles’. In terms of managing and making operational versus tactical versus strategic decisions, the major factors to be addressed depend on the producer’s situation. For example, rain-fed production as compared to irrigated management. In a rain-fed environment, the big management factors include: drainage (surface and internal), soil erosion (resulting from mechanical soil and crop residue management), pH, soil nutrients and compaction. Under irrigated conditions, the major factors include: water management (both land preparation and irrigation water distribution) and residue management (which affects both surface and internal soil water flow). The other important factors in irrigated agriculture include compaction, soil nutrients, pH, and salinity.

When approaching management changes, producers must perform qualitative assessments of their operations. They should undertake this mental journey before making any purchases of software or equipment. Simply think about a field or an area, gathering and summarizing all the information available. Use available soils maps, imagery downloadable from the Internet free of charge, and/or create

Table 1.2 Qualitative assessment example

Problem	Yield variability	Complexity of addressing the problem	Expected yield increase [%]	Expected payback (year)
Low spot (topography)	High	Hard (level the field)	10	4
Soil pH	Low	Easy (variable rate liming)	5	7
Sandy patches	High	Medium (variable rate seeding and fertilization)	20	1

hand-drawn maps based on personal experience. Next, draw a map of the changes anticipated once management is altered. As shown in Table 1.2, such information can be summarized using a template to see what problems to address first. Figure 1.9 shows potential factors that can cause inconsistent crop-growing conditions according to their influence on yield variability and complexity of remedy. Clearly the factors that fall in the lower right corner of this grid should be dealt with first.

Also, producers must keep in mind that yield maps are the ultimate illustrators of potential limitations associated with soil heterogeneity. Figure 1.10 shows the process one might follow in deciding whether to invest in site-specific crop management, based on analysis of yield maps. If yield variability across the field cannot

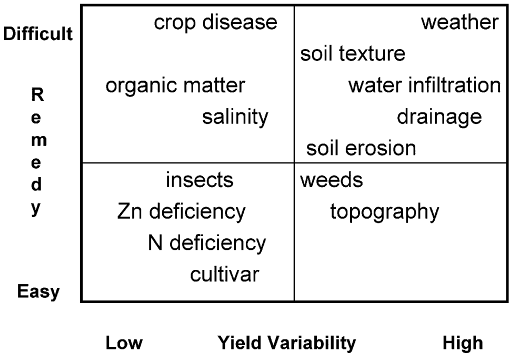

Fig. 1.9 Decision grid with factors that may affect soil heterogeneity in a given growing environment

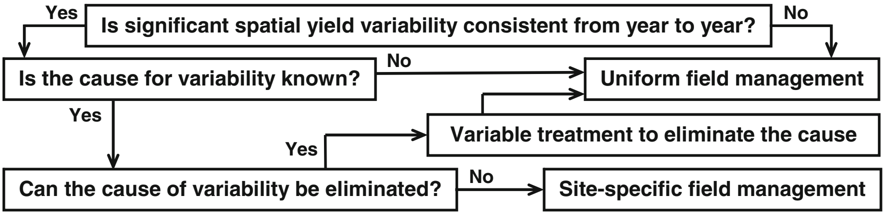

Fig. 1.10 Yield-based decision-making tree

be explained by any spatially inconsistent soil property, uniform management may be appropriate. Site-specific management becomes a promising strategy if yield patterns are consistent from year to year and can be correlated to a layer (or layers) of spatial data (e.g. nutrient supply, field topology, past management, etc.).

4 Summary

Soil heterogeneity is caused both by natural and management-induced processes, and can be described in terms of static and dynamic variables. The manageability of these variables is defined primarily using the rules of production economics. Producers must understand the sources of soil heterogeneity and be able to make qualitative, and, if appropriate, quantitative assessment of spatial variability in soils. If the potential benefits exceed the necessary cost and time needed to address soil heterogeneity, differentiated treatment of an agricultural field according to local conditions may be appropriate and can potentially improve economic and environmental outcomes of crop production. A variety of sensor-based technologies have been transitioning from research into production agriculture that may improve our understanding of soil heterogeneity and provide the technical means to optimize the crop growing cycle.

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